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Introduction to model-based teaching and learning in science education

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The value of models and modelling to traditional scientific research is well documented (Black 1962). Models are important in scientific research both in formulating hypotheses to be tested and in describing scientific phenomena (Gilbert, J. 1995). In the past decade the value of models and modelling to science education has been increasingly recognized among the science education reform movements (National Science Board Commission on Precollege Education in Mathematics 1983, Giere 1991, NRC 1996, AAAS 1993). At present, models and modelling are considered integral parts of scientific literacy (Gilbert and Boulter 1998, Gilbert, S. 1991, Gilbert, J. 1993, Linn and Muilenberg 1996, Perkins 1986).

With the recognized importance of models in science education comes the need for a theory of model-based learning and teaching. However, there is, to date, no coherent theory that outlines the cognitive processes involved in model-based learning, nor are there any coherent theories of how model-based teaching should be approached. The goals of the papers presented in this special issue and the symposium from which they were drawn are: to provide a sample of different research programmes that focus on model-based teaching and learning (MBTL), to highlight what we have learned from these studies and others, and to identify what we need to know in order to develop coherent theories of model-based learning and teaching.

At the outset, it is important to identify and define the key concepts and presuppositions underlying the set of papers presented herein. First, by models, we are using the general definition put forth by Ingham and Gilbert (1991): a model is a simplified representation of a system, which concentrates attention on specific aspects of the system. Moreover, models enable aspects of the system, i.e., objects, events, or ideas which are either complex, or on a different scale to that which is normally perceived, or abstract to be rendered either visible or more readily visible (Gilbert, J. 1995). We choose the word 'system' because models as representations sometimes add complexity, structure, and a level of explanation that is not inherent in the phenomena itself being described. For example, a model of heating air in a furnace is enriched when a layer of explanation involving molecular motion is added (Brown and Clement 1989). In further elaborating on models, it is important both in the existing literature, as well as in the papers

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presented herein, that we define the different types of models to which we refer. Our starting point is Norman's (1983) conception of models, all related to a target system or phenomenon, which is said to exist in common experience, and is to be represented or modelled. Norman also identifies the users' mental models and the researcher's or designer's conceptual models of the system, and the scientist's conceptualization of the user's mental models. By our focus on mental models we align ourselves with the position that people have, construct, and reason with mental entities called mental models (Johnson-Laird 1983). In addition to mental models that are personal internal representations of the target system being modelled, we define expressed models as external representations of the target generated from one's mental models and expressed through action, speech, written description, and other material depictions. We acknowledge the social construction of knowledge by defining consensus models as expressed models that have been developed, tested, and agreed among scientists or among groups of learners. Lastly, we include teaching models; these are developed and used by teachers and curriculum writers to promote the understanding of a target system. Our usage of model, then, is compatible with the constructivist view that knowledge must be built within the individual mind (von Glasersfeld 1987, 1995) as well as collectively in science and society (Vygotsky 1962).

With these definitions in mind, we define model-based learning as the construction of mental models of phenomena. We believe that the user in response to a particular task constructs mental models, then evaluates and revises them as needed. While it is impossible to know precisely the nature and content of mental models, even our own, we can as researchers draw inferences about the nature of one's mental models based on the types of reasoning learners are able to do with the knowledge they possess. Model formation, we assume, is the construction of a model of some phenomenon by integrating pieces of information about the structure, function/behaviour, and causal mechanism of the phenomenon, mapping from analogous systems or through induction. Use and evaluation of the model may lead the learner to reject their model and begin again or may trigger revision or elaboration. Model revision involves modifying parts of an existing model so that it better describes or explains a given situation. Model elaboration might involve combining or making additions to existing models by processes such as embedding a model in a larger system or adding more parts to the model (Clement 1989, Stewart and Hafner 1991).

Model-based teaching is any implementation that brings together information resources, learning activities, and instructional strategies intended to facilitate mental model-building both in individuals and among groups of learners. In some of the papers presented, namely, those by Rosaria Justi and John Gilbert, Allan Harrison and David Treagust, and Beverly France, the authors seek to characterize different types of expressed models that exist 'in the world', i.e. in classrooms, curricula and instructional programs, in order to develop working definitions and methods for studying the elements of model-based teaching. Issues presented in these papers largely concern students' epistemologies of models and of science and how science education might be altered to positively influence students' understandings of models and their role in science.

The papers by Barbara Buckley, Janice Gobert, and Jennifer Snyder focus primarily on model-based learning. Buckley and Gobert analyze their respective domains to delineate the types of knowledge that students need to acquire in order to obtain a rich understanding of the domain. The types of knowledge are described in terms of structure, function, behaviour and causal mechanism in the case of the circulatory system (Buckley). In the domain of plate tectonics (Gobert), the types of knowledge described are spatial, causal, and dynamic. In both cases, the papers deal with the role of representations of different types of knowledge in the domain and students' interactions with them. Buckley looks at learners using representations created by others to build models while Gobert examines representations generated by students. Both papers seek to characterize the nature of learners' models and the reasoning associated with these models.

The paper by Jennifer Snyder takes a more philosophical view, and in doing so combines work from the history and philosophy of science (Giere 1991) with a methodological approach developed in cognitive science in order to characterize how individuals with varying levels of expertise structure the domain of physics. The research question primarily addressed here is how do experts, sub-experts, and novices represent models and theories within the domain of physics.

Rosaria Justi and John Gilbert also deal somewhat with learners' representations and their potential interaction with physical representations because these authors trace the development of the theory of the atom through its various stages, i.e., its historical consensus models, and describe how it is used in curricular programmes presently. Their goal is not to identify reasoning, or problem solving *per se*, but rather to address the potential contributions to students' epistemologies of science and knowledge of science as a dynamic process of inquiry. As such Justi and Gilbert's paper addresses both model-based learning and teaching.

The paper by Harrison and Treagust presents a descriptive analysis of models in science education. In doing so, they identify and describe the many different types of models in science classrooms. The authors also have the goal of promoting epistemological development in students in that they want teachers and students to have a common understanding of the different types of models encountered in science and their respective purposes.

Lastly, the paper by Beverly France distinguishes models in science from models in biotechnology. Her claim is that scientific models are more general than biotechnological models in that their purpose is largely for illustration and explanation. Biotechnological models, on the other hand, fulfil a more specific role in that they are constructed in response to a particular problem-solving task whose solution must take into account social and economic factors.

While acknowledging the importance of the social and cultural contexts in which model based teaching and learning (MBTL) occurs, this set of papers focuses on the cognitive core of the phenomenon. Seeking to build a model of MBTL, we ask the initial questions: What are the elements of MBTL? How do they function in model-based teaching and learning? More specifically, we seek to address: What are different kinds of models? (Harrison and Treagust; Justi and Gilbert), how are these represented via mental models with respect to their form and function in reasoning (Buckley, Gobert, and Snyder), and how should models and modelling tasks be presented so as to promote a good understanding of the nature of models and their purpose in science instruction (Justi and Gilbert) and their purpose in biotechnology education (France). The researchers in this issue address these issues in a variety of contexts (biology, chemistry, physics, geology, and technology) and from a variety of perspectives (teaching, learning, and problem solving).

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